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**GLOBAL SENSING OF GASEOUS AND AEROSOL TRACE SPECIES
USING AUTOMATED INSTRUMENTATION ON 747 AIRLINERS**

by Porter J. Perkins and Leonidas C. Papathakos
Lewis Research Center
Cleveland, Ohio 44135

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GLOBAL SENSING OF GASEOUS AND AEROSOL TRACE SPECIES USING AUTOMATED INSTRUMENTATION ON 747 AIRLINERS

P.J. Perkins and I.C. Papathakos
NASA Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

The Global Atmospheric Sampling Program (GASP) operated by NASA is collecting and analyzing data on gaseous and aerosol trace species in the upper troposphere and lower stratosphere. Measurements are obtained from automated systems installed on four 747 airliners flying global air routes. Since the introduction of this program in 1975, advances have been made in airborne sampling instrumentation. Improved instruments and analysis techniques are providing an expanding data base for trace species including ozone, carbon monoxide, water vapor, condensation nuclei and mass concentrations of sulfates and nitrates. Simultaneous measurements of several trace species obtained frequently can be used to uniquely identify the source of the air mass as being typically tropospheric or stratospheric. A quantitative understanding of the tropospheric-stratospheric exchange processes leads to better knowledge of the atmospheric impact of pollution through the development of improved simulation models of the atmosphere.

AUTOMATED AIR SAMPLING SYSTEMS installed on four 747 airliners were reported at the Third Conference on Environmental Sensing when these systems first became operational in 1975 (1)*. Since that time improved instrumentation has been added. This paper describes this improved instrumentation and presents some in-flight measurements which illustrate the ranges and inter-relationships of the data from these instruments. Brief descriptions of the NASA Global Atmospheric Sampling Program (GASP), and the airborne system in which this instrumentation is used are also included.

Air sample measurements have or will include the concentrations of ozone, carbon monoxide, water vapor, nitric oxide, and chlorofluoromethanes. In addition to these gases, the number density of condensation nuclei and the concentrations of sulfates and nitrates are also measured. During the initial two years of operation, a large data base on atmospheric ozone concentrations at airline cruise altitudes has been obtained. The other air sample measurements have required a more extensive development effort for airborne use. Data bases for these trace species are beginning to evolve.

The GASP effort was initiated to provide baseline information on atmospheric constituents which could be used with other data sets and with computer models to assess the effects of aircraft exhaust emissions on the upper atmosphere. This assessment effort was prompted by studies conducted several years ago (2) (3). The results of a more recent study (4) predict a lesser effect of aircraft emissions on atmospheric ozone. Nevertheless, this latter study does recommend and suggest continued research in certain problem areas, including studies of the dynamics in the region of principal aircraft traffic. It also recommends the simultaneous measurement of the concentrations of the several species critical to ozone destruction. Apart from the ozone problem, simultaneous measurements of several trace species can uniquely

identify the source of the air mass as being typically tropospheric or stratospheric. Quantitative information on the tropospheric-stratospheric exchange processes when applied to simulation models of the atmosphere provides a better understanding of the impact of pollution on the atmosphere.

PROGRAM DESCRIPTION

The airlines that are presently participating in GASP in this global study are shown in figure 1. This figure shows 747's of United Airlines, Pan Am, Qantas Airways of Australia, and another Pan Am 747-SP (a new long range, higher altitude Special Performance version of the 747). These airlines were chosen to provide coverage of major global air routes, as shown in figure 2. The NASA Convair-990 flying laboratory is also equipped with a GASP system. The CV-990 is used to survey off-airline routes. A recently completed latitude survey mission over the Pacific (5) is one example.

United Airlines flies principally over the United States, coast to coast and to Hawaii. Pan Am flies around the world and to South America. Qantas, based in Sydney, flies frequently to Europe and to the West Coast of the United States.

GASP air constituent measurements and supplemental data are listed in Table I. Ozone, water vapor, nitric oxide and carbon monoxide are measured with in-situ instruments. Chlorofluoromethanes and other trace species can be obtained from laboratory analyses of bottle samples captured in flight. The number density of particles greater than 0.3 micrometer dia. measured with the light-scattering technique, and smaller particles called condensation nuclei measured with the cloud-chamber technique, are also in-situ measurements. Mass concentrations of sulfates and nitrates are determined from laboratory analysis of filter paper samples exposed in flight.

At the time of each air constituent measurement, certain supplemental data are recorded (Table I). Time and position of the aircraft, its altitude, speed, and direction pinpoint each air constituent measurement. Data related to meteorology are also taken. Air temperature, horizontal wind direction and velocity, and an indication of turbulence as measured by the vertical acceleration are recorded. The light-scattering instrument for measuring the larger particle sizes also responds to the presence of clouds in the flight path as determined during flight tests.

Each GASP-equipped aircraft flies about 10 hours per day, for a total of about 8700 km (5400 miles) each day or about 13 million km (8 million miles) per year for the four 747's. A data set is recorded every 5 minutes or about every 72 km (45 miles).

Field service of the GASP equipment and necessary support by the airlines are managed by United Airlines Engineering Group under contract to NASA Lewis. GASP data retrieved by airline personnel from the aircraft are sent to NASA Lewis for processing and finally, are transmitted to the users for detailed analysis.

The data preparation begins with the routine service check of the GASP system on the aircraft and the removal of the data recorded on a tape cassette. The information on the cassette is transcribed onto computer-compatible tape by United Airlines. NASA Lewis then does the data reduction and preliminary analysis. The tropopause pressure fields from the National Meteorological Center and the results of the

*Numbers in parentheses designate references at the end of paper.

bottle samples and filter sample analyses are added to the final data tape as part of the data reduction process. While the final tape is being prepared at NASA Lewis, a report is written describing the availability of the data and some of their selected highlights. As a last step, the prepared tape is sent to the National Climatic Center for archiving and to NASA contractors for detailed analyses. The availability report is mailed to members of the scientific community concerned with the atmosphere.

AIRBORNE SYSTEM DESCRIPTION

Location of the GASP equipment in the 747's is shown in figure 3. The installation is near the nose below the passenger deck. Two air sample inlets mounted in a single strut sample both gases and particulates outside of the aircraft's boundary layer very near the nose. One of the inlets is designed for isokinetic sampling for measuring particle number density. Both inlets are capped when air samples are not being taken.

Air flows from the inlet in a 25.4 mm (1-inch) diameter tube aft to the instruments where pressurization is required for ozone and carbon monoxide measurements. A rack mounted to the airframe holds most of the GASP instruments, as shown in figure 3. The instruments are packaged in standard airline avionics cases. Air is also ducted in a 76 mm (3-inch) diameter tube from the inlet to the other side of the aircraft, where a mechanism is located for exposing the particle filter papers. This mechanism is similar to a slide projector and holds eight filters that are exposed individually at preselected intervals. Two of the four 747's are equipped with the particle filter system.

GASP system control and data management and acquisition are performed by three separate units. Automatic control of all system operations and management of all data are functions of a data management and control unit. This unit contains a small special-purpose computer preprogrammed to respond to independent aircraft inputs and to operate the instruments. Most of the data are acquired by the second unit which is a conventional airline flight data acquisition unit. Data from the GASP instruments and other parts of the system, as well as from the aircraft systems, flow to this unit. Position and horizontal wind data come from the aircraft's inertial navigation system. All data are recorded on magnetic tape contained in the third unit which is a digital airborne recorder. The tape cassettes from the recorder are replaced about every two weeks.

Total weight of the installed system is about 380 kg. All equipment meets FAA certification requirements, and the entire installed system was flight tested during a special flight following which a Supplemental Type Certificate (STC) of airworthiness was issued for the GASP system. Operation is completely automatic, requiring no attention by the flight crews. A more complete description of the operation of the airborne atmospheric sampling system is given in reference 1.

INSTRUMENTATION

The GASP in-situ measuring instruments, their operating principles, and range are listed in Table II. These are basically laboratory instruments with significant range improvements and modifications to operate in a commercial airline environment. Such modifications involve packaging to airline specifications and the ability to withstand a high use factor. Figure 4 illustrates a GASP instrument packaged to airline standards. Two conventional airline avionics cases are used in packaging the carbon monoxide instrument

as shown. Other instruments can be contained in only one airline type case. Size and weight of each avionics case are held to a minimum for convenience in handling.

Existing commercial instruments used to measure carbon monoxide, oxides of nitrogen, and condensation nuclei were significantly improved to measure the very low concentrations in the upper atmosphere. Descriptions of these instruments follows.

CARBON MONOXIDE - A modified Non-Dispersive Infrared Absorption analyzer is used to measure CO. In this instrument fluorescence from two isotopes of CO ($C^{12}O^{16}$ and $C^{12}O^{18}$) is used as the source of infrared energy. The two IR radiation spectra are alternately allowed to enter the sample chamber. The $C^{12}O^{16}$ in the air sample (98.9% of all naturally occurring CO is $C^{12}O^{16}$) will absorb this common isotope radiation but not the $C^{12}O^{18}$ radiation. The ratio of these two signals from an IR detector is a measure of the CO concentration in the sample chamber.

The original CO analyzer using the dual isotope fluorescence technique had a full scale range of 20 parts per million (ppm). Modifications to provide the sensitivity needed for GASP included an increase in the optical path length to 10 meters, special reflective optics, and additional electronic gain. These improvements provided a 1 ppm full scale sensitivity with a limit of detectability of 0.02 ppm of CO.

In-flight checks on this instrument include a zero reading (sample is passed through a catalytic CO scrubber) and an electronic gain check. These checks are automatically sequenced with atmospheric CO measurements by the on-board GASP programmer.

CONDENSATION NUCLEI - This instrument measures the number concentration of very small airborne particles (nuclei) on which water vapor condenses in a cloud chamber. The attenuation of a light beam by the cloud in the chamber is a measure of the number concentration. The minimum detectable limit for this instrument was extended from 300 nuclei per cc to 30 nuclei per cc. This was achieved by improved sensitivity and a built in pressurization system with a pressure ratio of approximately 4 to 1 to concentrate the sample. A simple air piston consisting of a 3 meter length of 1.1 cm I.D. tubing is used for the gas pressurization system. A low pressure air sample from outside the aircraft is drawn into one end of tube. Pressurized aircraft cabin air filtered free of nuclei is introduced into the other end of the tube behind the low pressure air sample, thus compressing it. The pressurized air sample is drawn from the original inlet end into the cloud chamber of the instrument. With an appropriate sequence of valving this pressurization system can be used for sampling air flow rates of 5 to 50 cc/sec. In-flight checks on this instrument include a zero (using a filtered sample) and a check of the electronic gain.

NITRIC OXIDE - A very high sensitivity chemiluminescent analyzer is used to measure nitric oxide. The very high sensitivity is achieved, in part, by using a high sample flow rate (500 std cc/sec), a special technique for an in-flight zero measurement, and a nitric oxide calibration gas carried with the instrument for a span measurement. The instrument also contains an ozone generator of the silent discharge type. This is a modification of the previously developed high sensitivity instrument which used a bottled ozone mixture instead of an ozone generator (6). The self-contained ozone generator is necessary for the GASP field service frequency of every 2 weeks, since an ozone mixture in a bottle of practicable size would need more frequent replacement. The complete instrument is housed in two airline avionics

cases. Flight tests of the instrument have been completed and installation on the 747 aircraft are scheduled for early 1978.

CONCENTRATIONS OF SULFATES AND NITRATES - These measurements are made by laboratory analysis of filter elements exposed earlier in-flight and returned to NASA. A filter element is automatically inserted into the 76mm diameter air sampling duct for two hours and retracted into a magazine by an actuator assembly developed at NASA. Airflow through the filter during exposure is measured by a venturi unit. Each filter (IPC cellulose fiber) is enclosed in a stainless-steel holder under clean room conditions to minimize contamination. Filter elements are assembled in an eight unit replaceable holder magazine thus allowing several filter exposures between field service periods for the GASP system.

Since generally less than 30 micrograms of any one ionic constituent is collected on an exposed filter element, very sensitive methods of laboratory analysis are required. Ion chromatography is used to meet this requirement. Clean room procedures and filters that are carefully purified prior to exposure are necessary to utilize the high sensitivity of the ion chromatography analysis method. A more detailed description of this method is given in reference 7.

OZONE, WATER VAPOR, AND PARTICLES - Ozone has not presented a measurement problem although much care is needed to provide accurate results. Water vapor was initially measured with an aluminum oxide sensor. Excessive time response to changes in temperature and humidity (particularly from a saturated to an unsaturated condition) limited the amount of valid data obtained with this type sensor. Therefore, this instrument has been replaced with a cooled-mirror frost point hygrometer having a three stage thermoelectric cooler. Flight tests have shown better operating characteristics and a faster time response. Installation of this sensor on all GASP equipped 747 aircraft will be complete by the end of 1977. Aerosol particles greater than 0.3 micrometers in dia. have been measured with a light scattering type sensor. Experience with this instrument has shown a large variability of number density and size distribution. Laboratory calibrations of the instrument have revealed a large uncertainty in the absolute measurement of number density as well as size distribution. An improved instrument is being investigated. Flight test experience with this instrument indicated, however, that flight through a cloud resulted in a particle size distribution that is significantly different from that of a clear air sample, mainly in the total count of the largest size particles. A simple cloud detector is therefore obtained by observing the counting rate of the largest size particles.

TYPICAL FLIGHT MEASUREMENTS

Examples of GASP atmospheric measurements taken simultaneously with in-situ instruments are shown in figures 5 and 6. These data were obtained on the GASP equipped UAL 747 airliner where a data set is normally recorded every five minutes.

Simultaneous measurements of ozone, carbon monoxide, condensation nuclei, air temperature, and altitude are plotted against longitude in figure 5 for a flight from Los Angeles to Honolulu. Ozone values under 150 parts per billion by volume (ppbv) shown in figure 5 are indicative of flight in the troposphere. Carbon monoxide concentrations between 100 and 200 ppbv are also characteristic of upper altitude tropospheric air. Condensation nuclei number densities, shown under 300 per cc, are relatively low compared to ground level measurements demonstrating the requirement

for the improvements to the minimum detectable limit for this instrument. Somewhat higher values are noted on ascent from 6 km to cruise altitude.

Ozone values over 800 ppb v shown in figure 6 are indicative of flight in the stratosphere. These were encountered during a flight from Seattle to Chicago. Carbon monoxide values are lower than those measured in the troposphere shown in figure 5. Values are in the order of 50 ppb v, which is consistent with previous measurements (8). This demonstrates the need for a low detectable limit and high sensitivity for this instrument also. During descent (figure 6) the rapid decrease in ozone and increase in carbon monoxide indicates that the airliner passed from the stratosphere into the troposphere before the GASP system shut down.

Simultaneous measurements of several trace species as shown in these figures can be used to uniquely determine the source of the air mass, as being typically tropospheric or stratospheric. A quantitative understanding of the tropospheric-stratospheric exchange processes is required for development of improved simulation models of the atmosphere and thereby a better knowledge of the impact of pollution on the atmosphere.

CONCLUDING REMARKS

Considerable effort has been required to develop airborne environmental instrumentation suitable for automatic unattended operation on commercial airliners. Existing laboratory type environmental measuring techniques were significantly modified to measure the very low concentrations of trace species in the upper atmosphere.

A carbon monoxide analyzer of the dual isotope fluorescence type with an original full scale range of 20 ppm attained a greatly improved sensitivity with a reduced full scale range of 1.0 ppm. With this sensitivity and an improved limit of detectability of 0.02 ppm, values in the order of 0.05 ppm were measured in the stratosphere. Improvements to the condensation nuclei instrument have resulted in a ten fold decrease in the minimum detectable limit for measurement of very small airborne particles. A high sensitivity chemiluminescent nitric oxide analyzer has been acquired, flight tested, and is scheduled for acquiring data on the 747 airliners in early 1978.

Simultaneous measurements of several trace species in flight at cruise altitudes aid in identifying tropospheric or stratospheric air masses, which can lead to quantitative information on tropospheric-stratospheric exchange processes.

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TABLE I.
AIR CONSTITUENT MEASUREMENTS

GASES

OZONE
WATER VAPOR
OXIDES OF NITROGEN
CARBON MONOXIDE
CHLOROFLUOROMETHANES

PARTICULATES

NO. DENSITY ($>0.3 \mu\text{m}$ DIAM)
CONDENSATION NUCLEI
MASS CONCENTRATION OF
SULFATES
NITRATES

SUPPLEMENTAL DATA

FLIGHT DATA

TIME & DATE
LATITUDE
LONGITUDE
ALTITUDE
AIR SPEED
HEADING

METEOROLOGICAL DATA

OUTSIDE AIR TEMP
WIND DIRECTION
WIND VELOCITY
TURBULENCE (VERTICAL ACCEL)
CLOUD ENCOUNTERS

TABLE II.

GASP MEASURING INSTRUMENTS

OZONE	ULTRAVIOLET ABSORPTION PHOTOMETER RANGE 3 ppb TO 20 ppm
WATER VAPOR	COOLED MIRROR HYGROMETER DEW-FROST POINT RANGE -80° TO $+20^{\circ}$ C
CARBON MONOXIDE	INFRARED ABSORPTION ANALYZER RANGE 0.02 TO 1 ppm
NITRIC OXIDE	CHEMILUMINESCENT ANALYZER RANGE 0.05 TO 10 ppb
PARTICLES ($D > 0.3 \mu m$)	LIGHT SCATTERING SENSOR
CONDENSATION NUCLEI	CLOUD CHAMBER MIN. CONCENTRATION $30/cm^3$

CS-77-406



IN SERVICE, DEC 1974



IN SERVICE, MAR 1975



IN SERVICE, NOV 1975



IN SERVICE, MAR 1976

Figure 1. - Airline 747 aircraft participating in NASA global atmospheric sampling program.

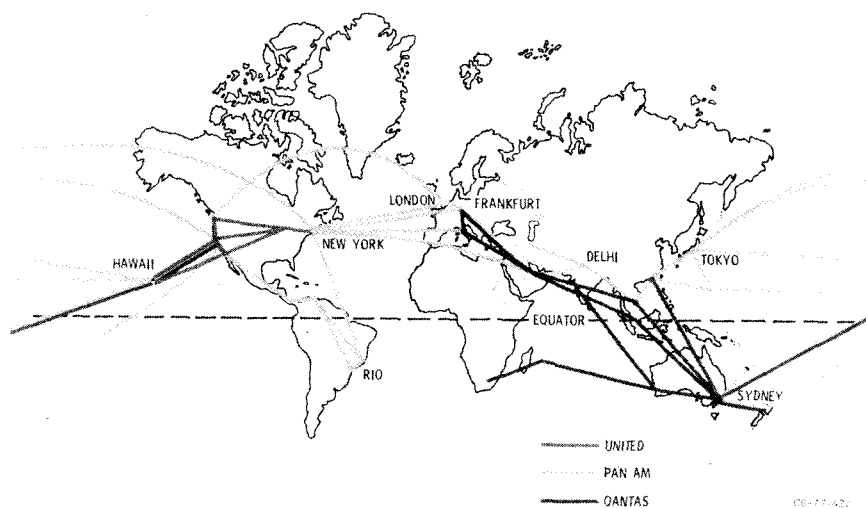


Figure 2. - GASP route structure.

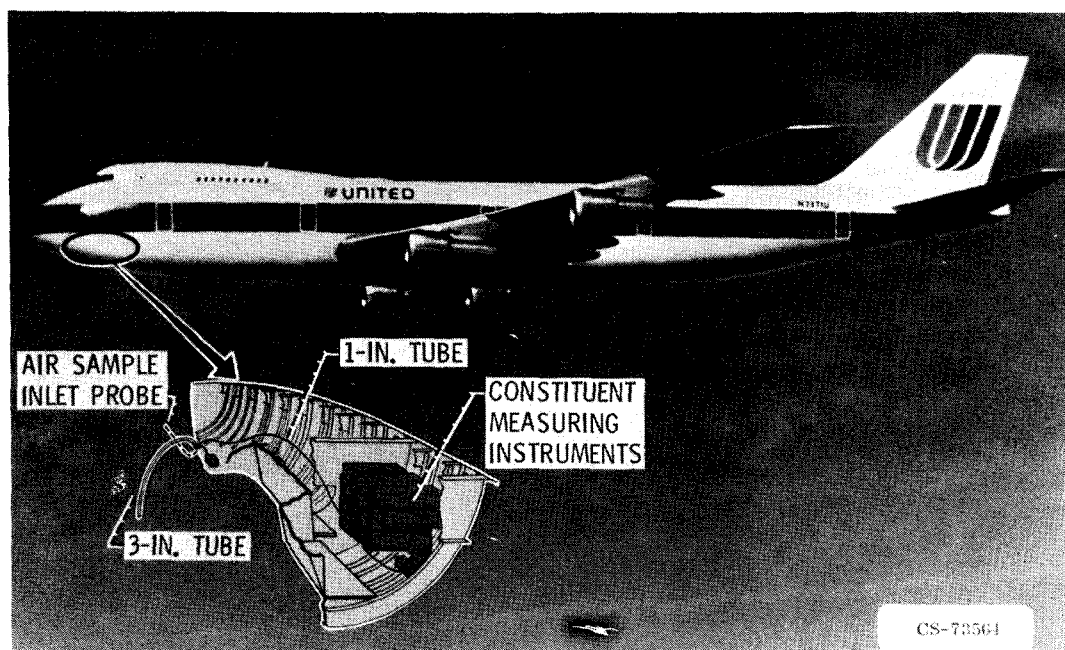


Figure 3. - GASP system installation.

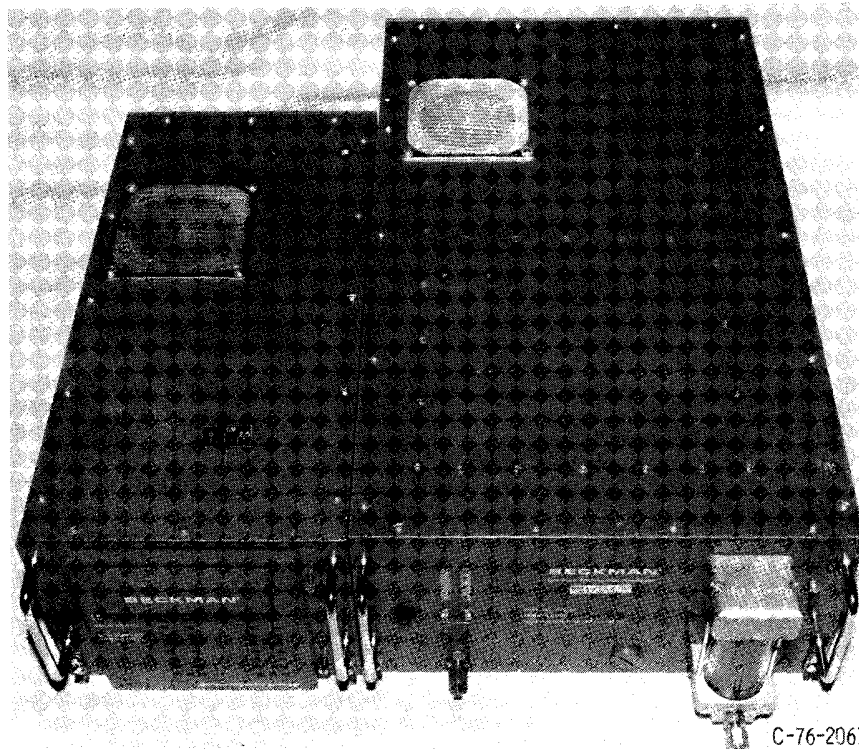


Figure 4. - An airborne GASP instrument (carbon monoxide analyzer) packaged in two avionics cases.

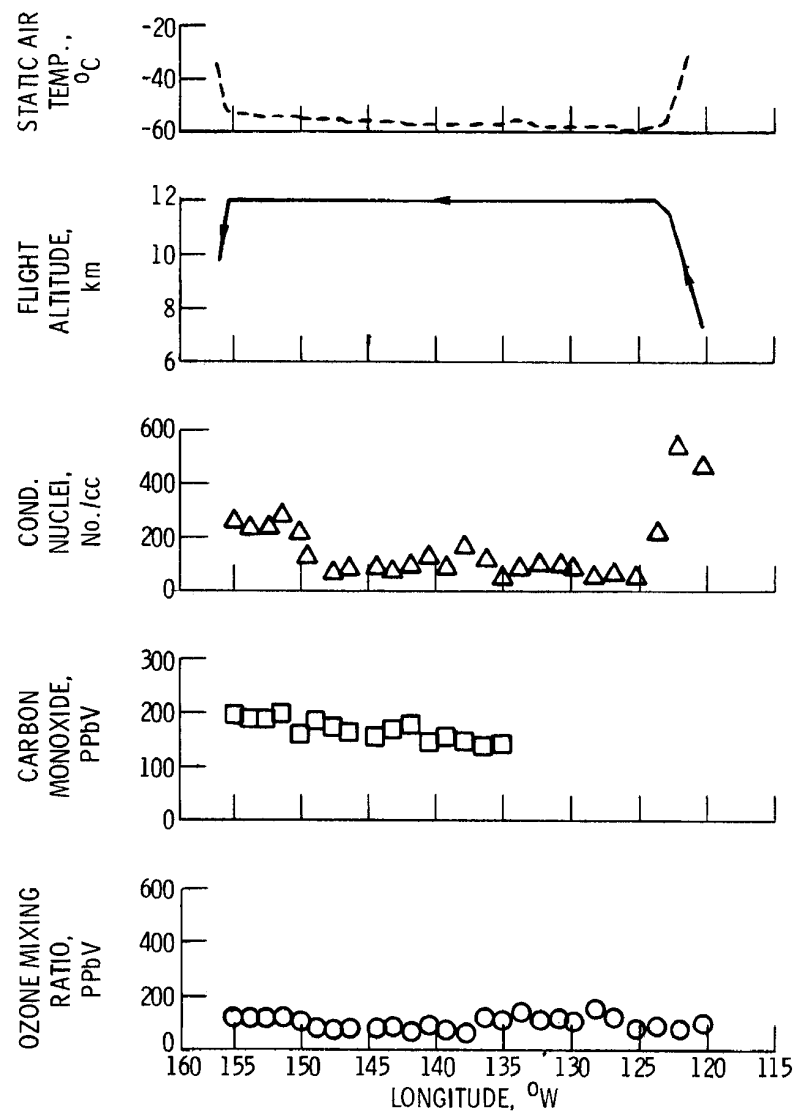


Figure 5. - Simultaneous measurements of ozone, carbon monoxide, condensation nuclei, and air temperature obtained with GASP instruments during a flight from Los Angeles to Honolulu.

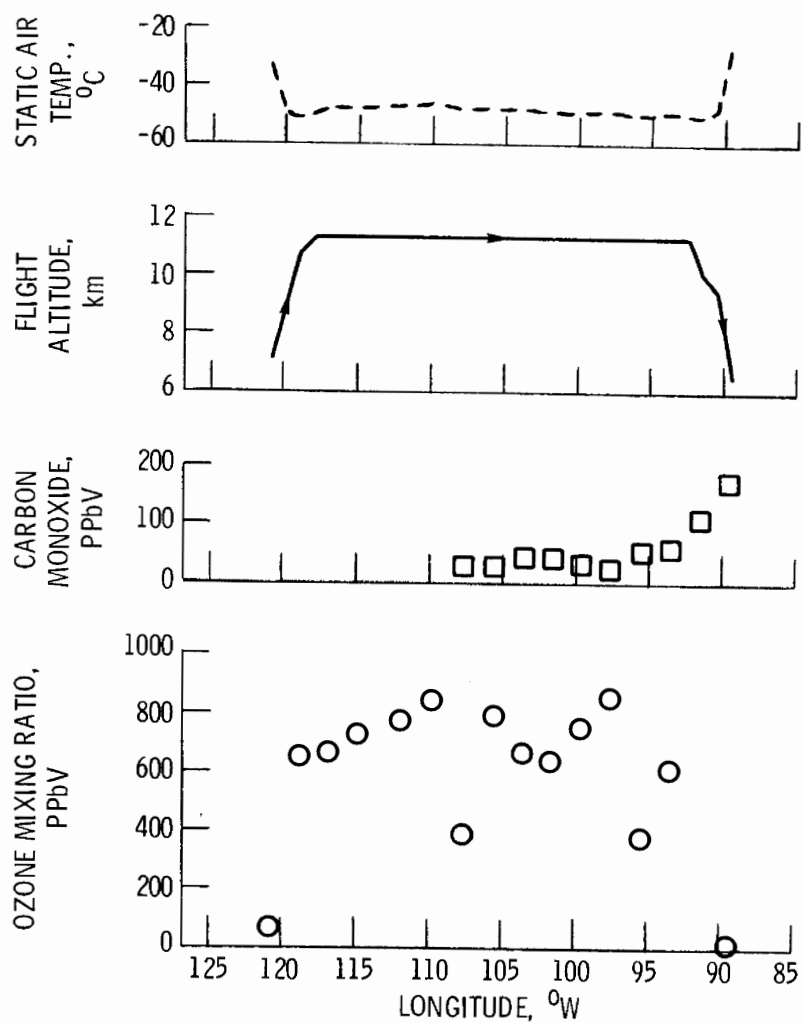


Figure 6. - Simultaneous measurements of ozone, carbon monoxide, and air temperature obtained in the stratosphere with GASP instruments during a flight from Seattle to Chicago.